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A DISPLACEMENT OR VELOCITY SERVO AMPLIFIER

REPORT
1015

RADIATION LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE - MASSACHUSETTS

NDRC
Div. 14
OEMsr-262

Radiation Laboratory

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A DISPLACEMENT OR VELOCITY SERVO AMPLIFIER

Abstract

A servo amplifier designed for use with a Diehl FPE-49, two phase, 60 cps induction motor is described. It can be used either as a displacement or velocity servo since input circuits adaptable to either usage are provided. The unit is designed for a maximum usable power of 50 watts with high stability and accuracy. Emphasis has been placed on ease of adjustment and maintenance.

W. Roth

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Title Page
14 Numbered pages

I. Introduction.

The majority of reder treiners have been designed to obviate the necessity for employing flying aircreft or moving ships in order to train personnel in the use of actual service radar equipment. To make this possible, the trainers must simulate the eircraft or ships in a realistic manner so that a considerable portion of the total training time cen be done at centrel fixed landbased installetions.

The problem therefore, is one of designing trainer equipment which cen duplicate reelisticelly the principal motions and characteristics of the units to be replaced. For instance, in the cese of the eirborne rader training program, the trainer must simulete the motion end cherecteristics of e flying aircraft so that the seme problems that he will encounter when finally in the eir are presented to the student. The problem of suitable simuletion concerns itself with the practicebility of designing and constructing e computing mechanism which is cepable of duplicating the principal features of the replaced unit. Since these computers invariebly require the use of eccurate medium power instrument servo loops of both the displecement and velocity types, the unit to be described has been developed to serve as a highly accurate and stable servo emplifier which can be used for either one of the two functions.

A displecement servo is one in which the displecement of the output sheft is proportional to thet of the input shaft although at a considerably increased power level. A velocity servo is one in which the velocity of the output shaft is proportional to the displacement of the input sheft end again, et e considerebly increesed power level. A general discussion of introductory servo theory which may be helpful to those not too familiar with the subject cen be found in Radiation Laboratory Report No. 645-2.*

II. Design Considerations.

A fundamental design consideration is that the unit be flexible enough for use in many different trainers with varying load conditions. It must also be cepable of responding to slow, continuous input signals for some systems end fest discontinuous input signals for others. It must be as foolproof as possible with the emphasis on ease of initiel adjustment and maintenance but at the same time stable operation must not be sacrificed. These criteria are extremely stringent since it is the usual practice to design a servo system for one particular set of conditions. If a different set of conditions is encountered, a change of design is generally necessery since it is rare to find systems which can meet e wide variety of operating requirements.

Certain specific requirements were set forth which had e bearing on the cherecteristics of the emplifier end the power output. Although servo emplifiers for driving d-c motors ere usually simpler to build than those for use with a-c motors, this unit is required to work with very low noise output so that the commutator noise resulting from the use of e d-c or e series e-c motor could not be tolerated. Hence, e two phase e-c induction motor was decided upon, and the emplifier was designed to drive such e motor.

The power output requirement was set for e level of 50 watts which is sufficient for the largest loads encountered in trainer work. The motor eround

*The Q1-2 and Q-3 Servo Amplifiers. R.L. Report 645-2 by R.U. Fathe end W. Roth.

which the amplifier was designed is the Diehl two phase 60 cps FPE-49 induction motor. The nominal power output is roughly 12 watts with an input power to the control winding of 35 watts so that the excess reserve power is useful for high accelerations. It should be pointed out at this point that this large factor of safety in power output is made necessary by the requirement that the servo be useful under such varied operating conditions.

Thus to summarize, the requirements to be fulfilled by the servo unit are:

a) It must be capable of use with many varied types of load conditions.

b) It must work satisfactorily with inputs ranging from the slow continuous to the fast discontinuous types.

c) It must be easy to adjust and maintain.

d) It must be stable in operation.

e) It must be capable of 50 watts output power at 60 cps to drive a Diehl FPE-49 motor.

f) It must serve as either a displacement or velocity servo with high accuracy.

III. Theory of Design.

Since the servo must be used in many widely differing applications, the servo amplifier must have sufficient sensitivity for the most stringent requirement. It was thought that this could be met by designing the unit with the highest gain possible so long as the other requirements of stability and ease of adjustment etc. were not compromised. It is a general dictum that stability and gain are inverse to one another, i.e. stability suffers with an increase of gain and high stability necessitates lowering of the gain. A factor which greatly complicates the situation is that the motor which becomes part of the output stage, is actually a nonlinear element since its impedance is a function of speed. The impedance of a motor at very low speeds is small compared to that at high speeds. The answer to both these problems is the use of feedback, which is so often the answer to the designer's many and frequent dilemmas.

It is well known that the use of voltage feedback in an amplifier leads to greater stability and a reduction of output impedance.* The relation giving the output impedance with voltage feedback in terms of the output impedance without feedback can be shown to be:

$$Z_o' = \frac{Z_o}{1 + a_o B}$$

where Z_o' = output impedance with feedback

*See: Electronics-Millman and Seely---page 606 f.f.

Z_o = output impedance without feedback

a_o = total overall amplifier gain without feedback

B = fraction of output voltage fed back to input (B is positive feedback for degenerative)

From this expression it can be seen that as the feedback fraction B increases, the output impedance is reduced, becoming zero when the product a_oB equals infinity. Although this seems to answer the problem of low output impedance, a compromise must be made since, as the factor B increases to cause a decrease in output impedance, the gain of the amplifier with this feedback decreases in a similar manner. The usual expression is the same as that given above with the letters a_o' and a_o replacing the respective impedance symbols. Hence a choice of impedance and gain value must be decided upon in order that the proper feedback circuit be used.

With a low output impedance, the amplifier has a high degree of stability even when faced with loads varying in a discontinuous manner. Such a load might represent a gear chain with backlash or sticky gears.

Since a 60 cps output as well as high stability and ease of adjustment is desired, an a-c amplifier is indicated. Accordingly, the amplifier was constructed to have a minimum phase shift with maximum gain at 60 cycles and the frequency response was controlled in such a manner that high stability is afforded with the feedback loop connected. This necessitates low gain at the frequencies which result in large phase shifts so that the degenerative feedback loop cannot become regenerative at any frequency for which the amplifier gain is sufficiently high to permit the buildup of oscillations. Since the gain of the amplifier without feedback must be high, the usual precautions to minimize stray pickup must be taken. The use of interstage transformers frequently gives rise to pickup troubles so that the number of such transformers employed must be kept to a minimum.

Provision for the inclusion of antihunt networks must be made in order that the system be capable of high accuracy without an inherent tendency to oscillate. In the final design, these networks were included immediately before the first amplifier stage when used as a displacement servo amplifier. Thus, the error voltage from the error sensitive element is fed into the networks, the output from which is amplified and applied to the control motor. The sense of rotation of the motor is determined by the phase of the error signal since the constant phase winding of the motor is fed from the same power source as the error sensitive element.

When used as a velocity servo, auxiliary circuits must be included for reversing the motor according to the sense of the error and for comparing the input signal to that of a d-c error indicating element. This latter element is a tachometer that generates a voltage proportional to the speed of rotation of the servo motor. It was decided to employ a d-c tachometer generator when the amplifier is used as a velocity servo since the linearity of output voltage against speed of rotation for d-c tachometers is far superior to that for available a-c tachometers. The limit to the accuracy of the complete loop is determined by the linearity of the tachometer, so that much emphasis must be placed on this element in the system. At present writing, the linearity of

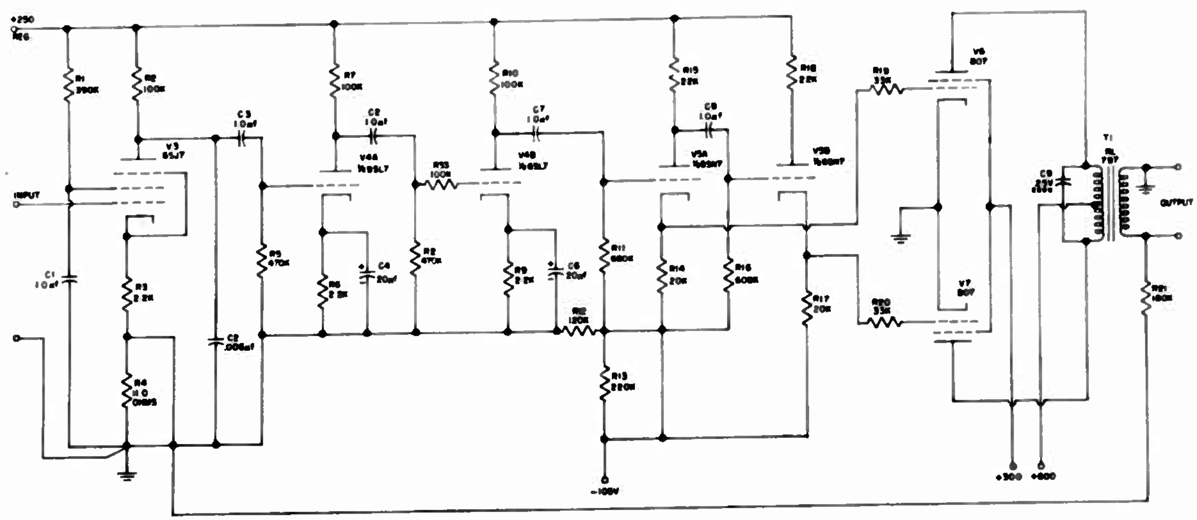

FIGURE I. AMPLIFIER CIRCUIT.

suitable tachometers runs in the order of ±1 percent. Better units are commercially available, although the voltage per RPM is quite low and the output noise level is high. The amplifier was made with a provision for including a tachometer superior to the one mentioned above in case such a unit could be obtained in the future. The actual linearity of the amplifier assuming a perfect tachometer is ±1/4 percent so that a considerable increase in over-all accuracy is possible if better tachometers do become available.

The input voltage which is used to control the speed of the servo motor is 60 cps a-c so that a linear rectifier must be included in order that the d-c voltage from the tachometer can be compared to the magnitude of the input voltage. The actual input voltage to the amplifier is a voltage proportional to the difference between the tachometer voltage and the input voltage. Since the amplifier is designed for 60 cps signals, the d-c voltage which represents the difference between the rectified input signal and the tachometer voltage is converted to a-c by means of a vibrator driven from the 60 cps line. Thus, to use the amplifier as a velocity servo, the input a-c voltage must be rectified, matched to that of the tachometer and the difference in d-c voltage must be converted by means of the synchronous vibrator before it is fed into the amplifier. A suitable antihunt network must be provided so that the velocity of the motor does not oscillate around its desired value. This network performs a function similar to that of the network provided for use with the displacement servo, although it stabilizes the velocity of the output shaft rather than its displacement.

Since the phase of the a-c voltage applied to the amplifier from the vibrator is controlled by the phase of the vibrator driving voltage and not by the phase of the input a-c voltage, the motor will have the same sense of rotation regardless of the input polarity. Therefore, means must be included whereby the motor can be reversed as the phase of the input voltage reverses. In order to fulfill this requirement, a phase detecting circuit is included to control the operation of a reversing relay which changes both the direction of rotation of the motor and the polarity of the tachometer voltage.

IV. Circuit Description.

A. The Amplifier.

The same amplifier circuit is used whether the unit is to be used as a displacement servo or as a velocity servo, although the input circuit and reference element used in each case is different. Therefore, the details of the actual amplifier circuit will be discussed first since they are common to both applications.

As discussed above, the amplifier is designed for very low phase shift at 60 cps with high gain and high stability. The input from either input channel (to be discussed later) is fed directly to the grid of tube V3, a 6SJ7. (See Fig. 1.) The stage is standard in all respects with the exception of the split cathode resistor. R4 has been included as part of the feedback loop to inject a fraction B of the output voltage into the input stage. The polarities are such that the feedback is degenerative and results in the low output impedance with high stability as discussed above. C2 has been included from plate to ground in order to reduce the gain of the amplifier at high frequencies. This is done to prevent high frequency oscillations. C1 is the screen bypass capacitor and has been included to increase the gain of the first stage by preventing screen degeneration. The gain of this stage without the feedback loop connected is approximately 20. The relatively low gain is caused by the cathode resistor R3 which has been left unbypassed.

The output voltage from this first stage is coupled by C3 to the grid of V4A. This stage is again conventional and needs no detailed discussion. Its gain is about 40. The signal is coupled by C5 to the grid of V4B which is identical to the previous stage with the exception of the series grid resistor R33. This exception is an important one since the response of the servo to short saturating signals is dependent upon the action of this resistor.

With the usual input signals, the level at the grid of V4B is well within the normal operating range of the tube. However if for some reason the signal becomes larger than normal, this grid will draw grid current since it is driven into the positive conducting region. If R33 were omitted, C5 would discharge during the positive conduction portion of the cycle and hence would develop a negative bias. Thus, when the signal returns to normal, the bias of V4B would be sufficiently negative to keep the tube cut off until C5 is recharged through R8. This means that the amplifier would be blocked until V4B were no longer below cut-off, and thus the servo would not follow the input signal which in turn would increase again. This process could develop into an uncontrollable block which, of course, results in poor servo response.

By including R33, the discharge current from C5 during the positive conduction time is reduced to such a value that the bias does not become sufficiently negative so that the tube is cut off. Hence, blocking is no longer possible except on abnormally long saturating signals which are not found in practice if the servo loop is properly designed. It was not necessary to include the limiting resistor in previous stages, since even with saturating signals the level is not high enough to cause grid conduction. The inclusion of R33 does not change the operation of this stage for normal signals and thus its gain is the same as the preceding stage, namely about 40.

It was pointed out in the preliminary discussion that transformers should be omitted wherever possible in order that instability due to stray pickup be minimized. Thus cathode followers are used to drive the 807 power output tubes rather than the customary transformer. Since a push-pull power stage is employed, two signals equal, but 180° out of phase must be developed by the driver stage. This is done by V5A and V5B.

The signal from V4B is coupled to the grid of V5A by C7. Both cathode and plate resistors are included and the values are so chosen that the voltage developed across the plate resistor R15 is exactly equal but opposite in phase to that applied to the grid. This signal is then coupled to the grid of V5B which is an identical stage. Hence, the signals on the respective cathodes are equal and opposite in phase. It is to be noticed that the negative return for these two stages is not ground but -105 volts. This is done to permit direct coupling from the cathodes to the control grids of the 807 tubes. By returning the cathode resistors to the negative supply, the d-c voltage on the cathodes with no input signal is the proper bias for the power tubes. This procedure results in a low impedance driver, in the order of 500 ohms, which is economical in space and weight and offers freedom from pickup difficulties.

Since the respective output signals and d-c biases should be approximately equal regardless of tubes chosen, the resistors used in the driver circuit are all 5 percent tolerance elements. This results in output voltages differing by not more than 10 percent independent of tubes. This is entirely satisfactory.

The power output stage is entirely conventional and needs little discussion here. The output transformer used was designed specially at the Radiation Laboratory to have a high impedance at 60 cps. Consequently, it has an inductance of 80 henries and matches the motor load of about 400 ohms to the output impedance of the push-pull 807's. The grid series resistors R19 and R20 are included to prevent the overloading of one of the power tubes. This might occur if much grid current were drawn since the two cathode followers are interdependent. If one of the 807 tubes were to draw much grid current, the d-c bias on the cathode of its cathode follower driver would change and this would affect the other driver. This action would lead to instability with large signals and so is undesirable. Although the series resistors limit the output power since the grids cannot drive into the positive region, the stability is increased and the obtainable output power of 50 watts is well within demand limits.

The secondary of the output transformer drives the control winding of the two phase Diehl motor, as well as supplying the feedback voltage for the first stage. This voltage is attenuated by the resistor network comprising R21 and R4 in order that the value of B be correct for the feedback desired. Since there is actually a very small shift through the amplifier at 60 cps, the feedback is not a pure real quantity. However, with the feedback loop connected, the phase shift from input to output is essentially zero, as well as can be measured, and the overall voltage gain of the amplifier across a 500 ohm load resistor is about 12,000. It is stable, and requires no adjustments of any kind in the amplifier channel itself. Maintenance should be restricted to tube failures only since conservative wattage ratings on elements have been used throughout.

B. The Input Circuit for a Displacement Servo.

The input circuit to be used when a displacement servo is desired is shown in Fig. 2. Two networks which are designed to physically fit into plug-in capacitor containers are shown. Thus, if networks with different constant are desired for a special purpose application, other similar units can be plugged into the available sockets. The first network shown is the phase lag network. It was mentioned that the constant phase winding of the two phase motor was excited from the line, which serves as the reference phase. For maximum power output from the motor, the control field should be excited by a voltage which is phased 90° to that of the reference phase. Since the amplifier has essentially zero phase shift, the input voltage must be phased 90° to the reference. The particular phase lag network shown in the figure is designed for a 114° phase lag when used with the associated parallel T network. With this phase shift and an input voltage source comprising a 5G and 5CT synchro combination, the output voltage will have the approximate 90° shift from the reference phase.

The parallel T network also shown in Fig. 2 is employed to introduce the proper derivative response which is necessary for stable servo operation. A

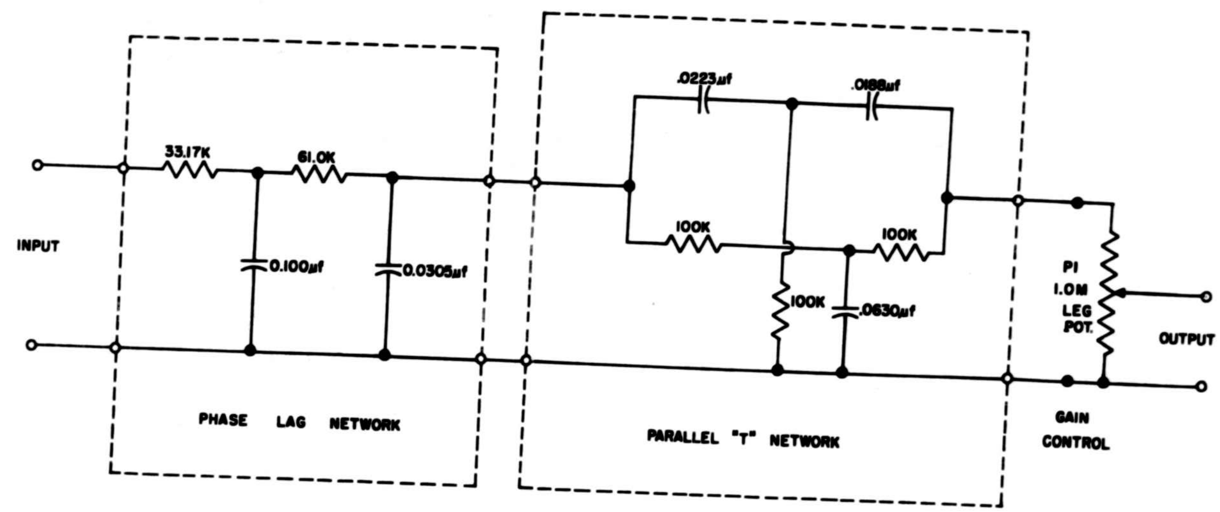

FIGURE 2. DISPLACEMENT SERVO INPUT CIRCUIT.

discussion of the principles of operation of such a network will be found in the previous reference, Report 645-2. Since the response of this network has a sharp dip at the carrier frequency of 60 cps, the higher harmonics present in the input signal come through the network with much less attenuation than the desired signal. This is sufficient to saturate the amplifier in many cases unless the higher harmonics are removed. The phase lag network shown also accomplishes this in addition to the previously stated purpose.

The only adjustment when the unit is used as a displacement servo is the gain control potentiometer P1. The signal present at the output of the parallel T network feeds the gain control P1 which has a logarithmic taper. The choice of taper was made so that the variation in gain per unit shaft displacement would be a constant. This is helpful in obtaining fine adjustment for critical applications. The output from the potentiometer feeds directly into the previously described amplifier unit. It should be emphasized here that since the two networks are plug-in units, for applications requiring different amounts of phase shift or different antihunt characteristics, other plug-in networks can be designed and substituted for the ones shown.

C. The Input Circuit for a Velocity Servo.

The input circuit for the unit used as a velocity servo is shown in Fig. 3. The circuit rectifies the incoming a-c signal, matches it against the voltage from the d-c tachometer and converts the difference back to 60 cycles a-c after including the proper antihunt characteristics. The rectifier, V2A, is a 6SN7 with the grid connected to the plate so that the tube operates as a diode. The rectified voltage appears across the network comprising C10 and R22. Since the load impedance is very high compared to the diode resistance, the rectification is linear to better than 0.1 percent. The lineerity could be improved if necessary, by increasing the value of the load impedance although a limiting value is reached when the time constant becomes so large that the d-c veriations cannot follow the variations in amplitude of the a-c input.

The rectifier is imperfect in that with zero volts input, approximately .5 volt of d-c is developed across R22. This is due to the contact potential of the diode, V2A. If the filament voltage for this tube were regulated so that this contact potential would be a constant, a small bias cell or a voltage derived from the B+ supply could be used to cancel the effect. However, this is not the case since the filament voltage does vary within the ±1 percent tolerance level permitted for normal tube operation. In order to cancel the contact potential, the second half of the tube, V2B, is connected as shown. Since this tube also develops a contact potential, it is possible to connect V2A and V2B in such a way that the two voltages cancel. If the plate of tube V2B is connected to its cathode by R23, the plate will be negative with respect to the cathode by an amount equal to its contact potential. Since the cathode of V2A is positive with respect to ground by an amount equal to its contact potentiel, the voltage at the plate of V2B with respect to ground will be the difference between the contact potentials of the respective tubes. By choosing a tube having a common heater for both sections, the temperatures of the respective cathodes remain approximately equal as the filament voltage varies. Thus, the net difference between the contact potentials will be very small since contact potential depends upon the difference in work functions of the cathode and plate which is largely a function of temperature. The actuel voltage obtained at the plate of V2B with zero volts a-c input is less than 0.01 volt

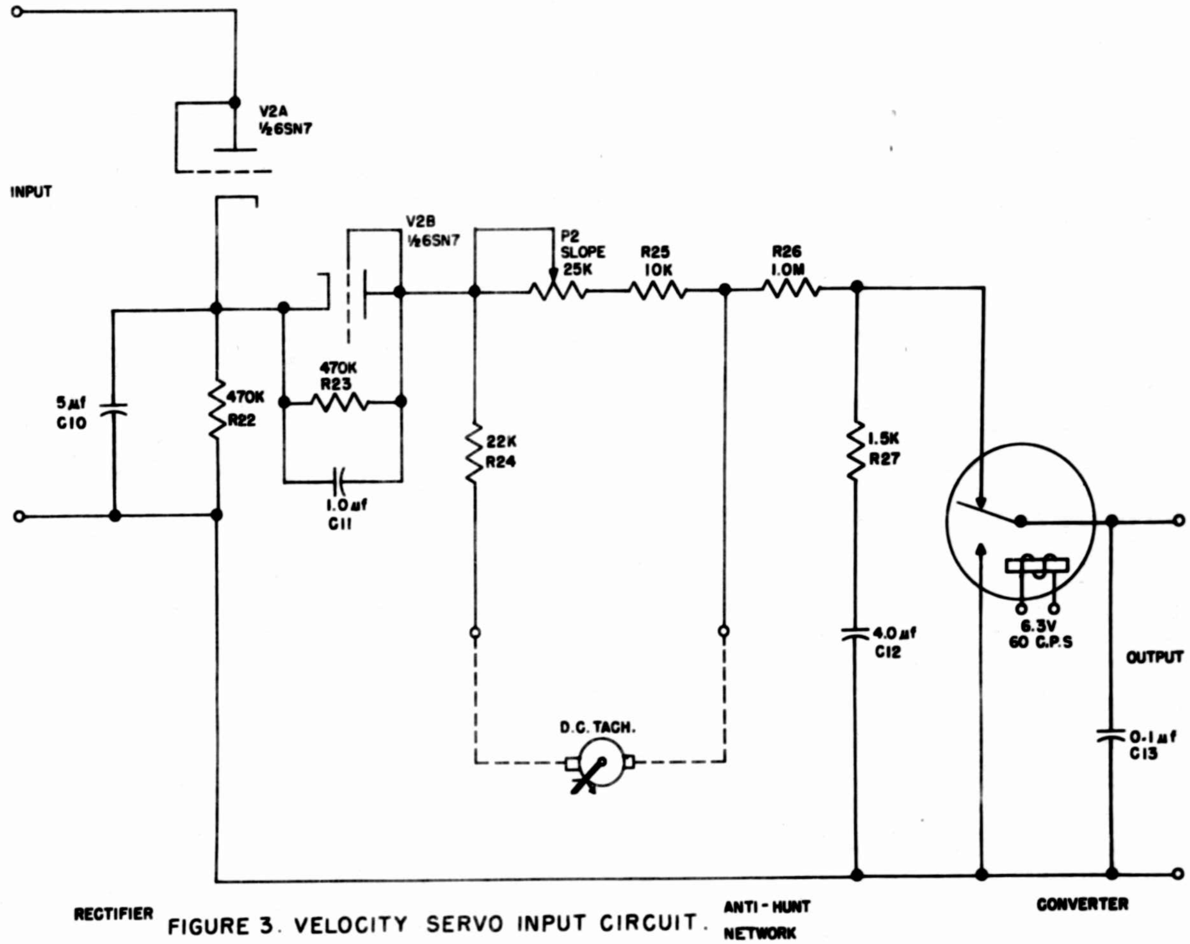

FIGURE 3. VELOCITY SERVO INPUT CIRCUIT.

as the filament voltage varies within its ±10 percent limits. C11 is included as a bypass for stray a-c pickup voltage which would be developed across R23. Hence, the effect of contact potential is made negligible so far as its influence on the velocity servo is concerned.

A fraction of the tachometer voltage is added in series with the rectified voltage as shown in the figure. R24, 25 and P2 comprise a voltage divider network. By changing P2, the voltage per RPM of the tachometer is effectively varied and this adjusts the output speed of the motor per unit input voltage. The polarity of the tachometer is such that the difference between the two voltages appears at the output of the network.

R26, R27 and C12 comprise a network which stabilizes the velocity of the motor. Since the response of such a network is unity at zero cps and falls off to a constant much less than unity at infinity, the emphasis is placed on the d-c component of the input difference voltage rather than on the a-c variations. This acts to stabilize the motor speed at the proper value by preventing any slight variations in speed from building up to an oscillating condition, which is the case when the network is removed.

The vibrator is driven by the 60 cps line so that the frequency of the output voltage will also be 60 cps. Actually the output voltage is a square wave which can be passed through the amplifier and applied to the motor without any detrimental effects. The amplitude of this square wave is proportional to the difference in d-c voltages between the rectified input and the tachometer. The speed of the motor will be stabilized at value which results in a difference voltage just sufficient to develop the power needed to drive the motor at that speed. The gain of the amplifier is such that this voltage is only 1/4 percent of the input voltage at the maximum motor speed. C13 is included to remove some high frequency components introduced by the vibrator contacts. The output from this channel feeds directly into the input terminals of the amplifier for use as a velocity servo.

D. The Phase Detector Circuit.

The remaining unit for discussion is the phase detector circuit as shown in Fig. 4. This circuit is employed to reverse the motor and tachometer leads when the phase of the input signal reverses, since the d-c rectifier discussed above does not include phase detecting means. The a-c input feeds into the grid of a high gain amplifier stage that has a gain of about 50. This is the same input that feeds the rectifier circuit and thus precautions must be taken to prevent any loading of the input voltage. If loading were permitted, the linearity of the unit would be decreased and the steps taken to eliminate contact potential would not be justified. By placing a large resistor, R28, in series with the input grid the loading is prevented since grid current is negligible.

The amplified voltage is applied to the grid of V1B whose plate load comprises the coil of a sensitive relay. The plate power is supplied by the 60 cycle line and thus serves as a reference phase. If the grid signal is out of phase with the alternating current on the plate, the tube does not conduct, but when the phase of the input is the same as that on the plate, the tube conducts heavily and the relay is actuated. The sensitive relay controls the power applied to a power relay and thus the power relay is actuated by the phase of

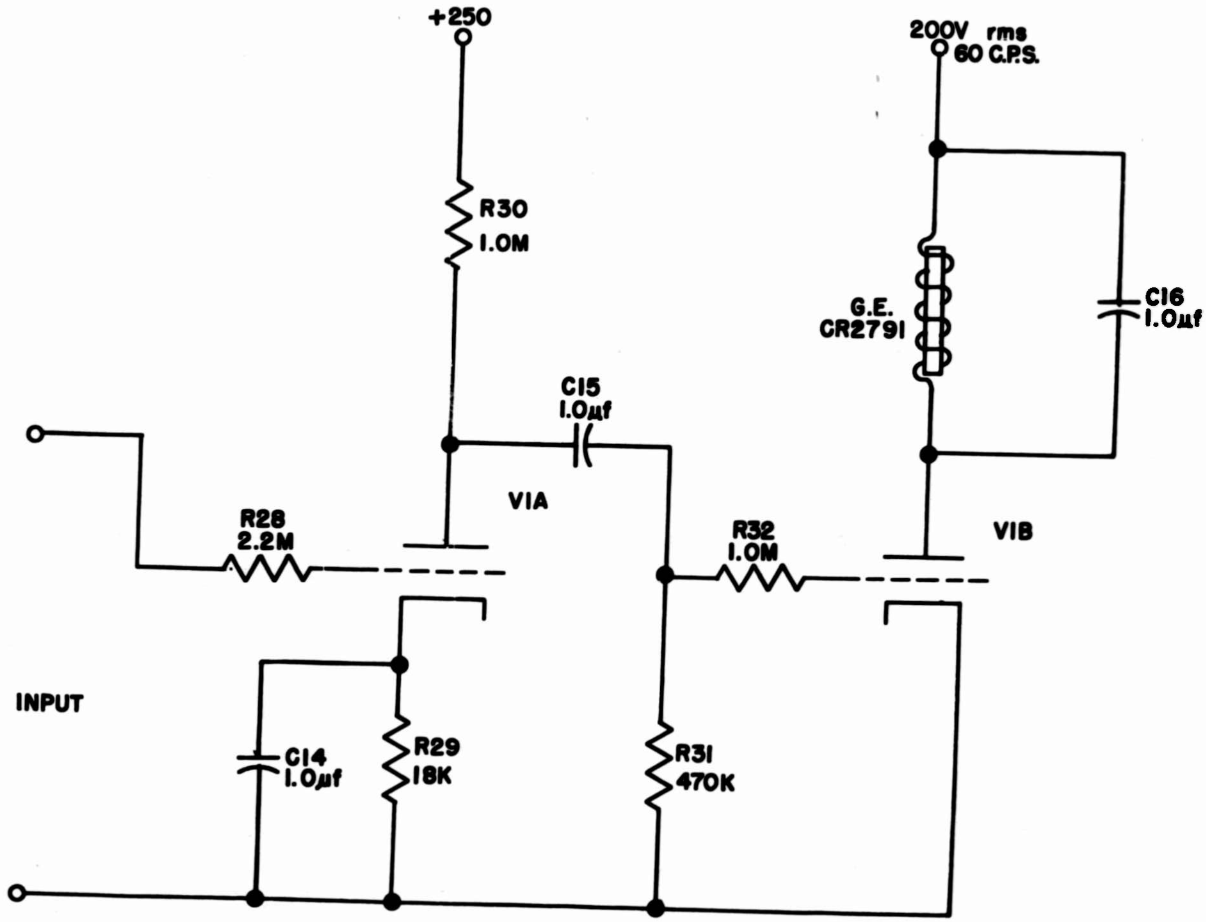

FIGURE 4. PHASE DETECTOR CIRCUIT.

the input signal, as desired. The power relay switches the leads of the control winding of the servo motor as well as those of the tachometer, so that the direction of rotation is made dependent upon the phase of the input a-c signal.

Figure 5 is a complete diagram of the unit including the switch which quickly converts from one input channel to the other. In some cases it is desirable to include a relay for the switching since it may be necessary to convert from one type of servo to the other by means of a panel switch.

Conclusion.

The original design criteris have been fulfilled by the unit described above. Complete testing in many different systems has not been done since work was stopped on this project after the completion of several units. However, preliminary tests have been made on a laboratory test jig containing a choice of several gear ratios between the motor and the error sensitive elements, either a 1CT synchro for a displacement servo or a d-c Elinco tachometer for a velocity servo. Provision for a variable friction load and variable inertia load were also included. Thus the laboratory test apparatus provided tests which could be made quite flexible and simulated most system applications. The operation of the unit in these tests was completely satisfactory.

Although the unit was to have a power supply included making it a completely self-contained servo amplifier, the project was stopped before this addition could be made. Certain construction precautions must be taken in order that the amplifier be free from oscillation tendencies and instabilities due to stray pickup. These precautions comprise such things as: a) making the filament leads to each tube, a tightly twisted pair of wires, b) using as a ground, a common wire grounded to the chassis at only one point grounding elements to the chassis, c) grounding the input lead at this common point after running two twisted leads from the error element, d) running two twisted leads to the motor after grounding one at the chassis ground, and so forth. These precautions, although conventional, cannot be overemphasized, since the gain is higher than is the case with most audio amplifiers and the tolerable noise level is much lower.

It was found that once adjustments had been made, only a single adjustment for either the displacement or velocity servo operation was necessary. Operation for roughly two hundred hours required maintenance of no kind, so that it would seem that the design allowed suitable factors of safety so far as tube and circuit element ratings are concerned.

W. Roth
November 5, 1945

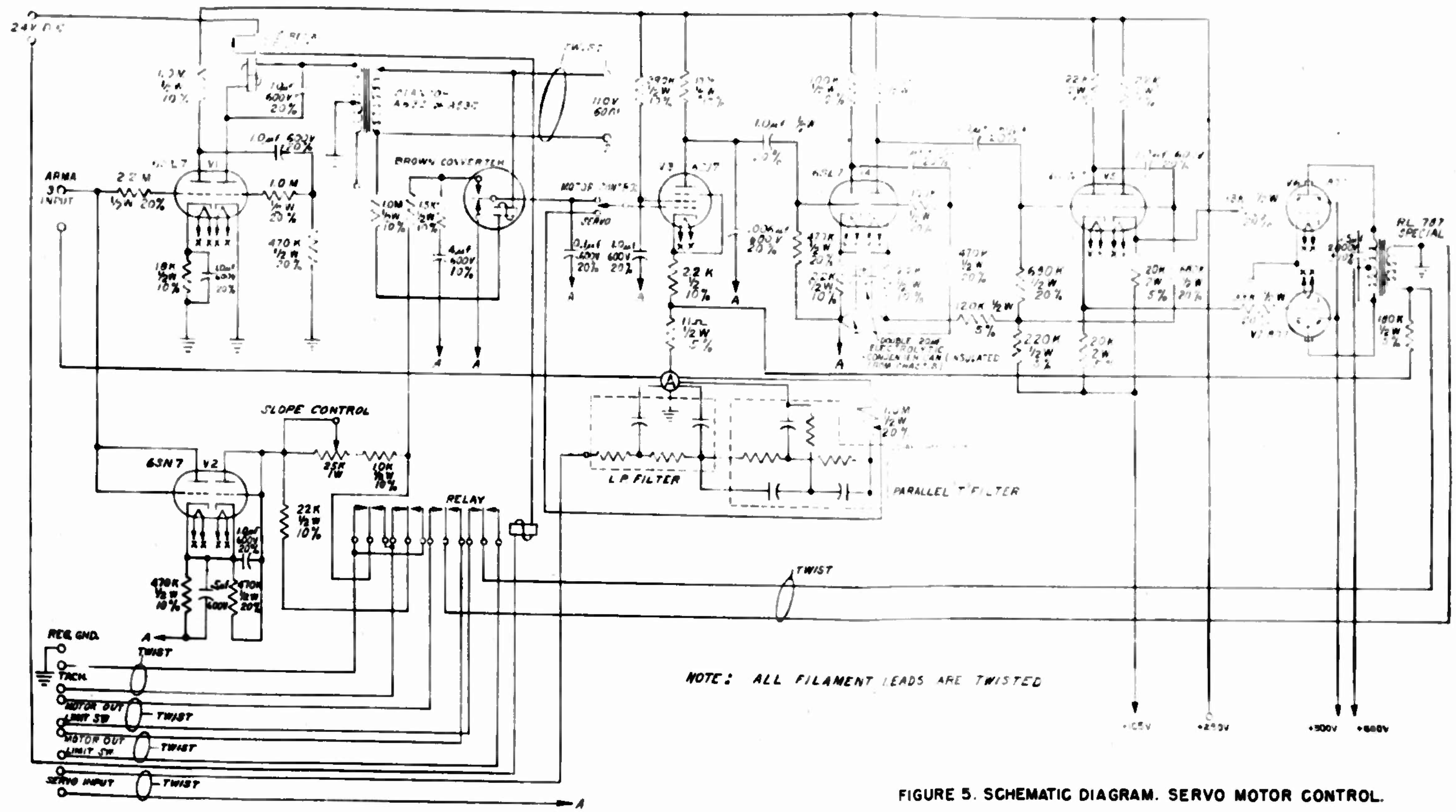

FIGURE 5. SCHEMATIC DIAGRAM. SERVO MOTOR CONTROL.

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A servo amplifier designed for use with a Diehl FPE-49, two-phase, 60-cps induction motor is described. It can be used either as a displacement or a velocity servo since imput circuits adaptable to either usage are provided. The unit is designed for a maximum usable power of 50 watts with high stability and accuracy. Emphasis has been placed on ease of adjustment and maintenance.

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